

Dark Energy in Chains

David Parkinson¹, Bruce A. Bassett^{1,2}, Edmund J. Copeland³, Pier-Stefano Corasaniti⁴ & Martin Kunz⁵

¹ *Institute of Cosmology and Gravitation, University of Portsmouth, Portsmouth, PO1 2EG, UK*

² *Department of Physics, Kyoto University, Kyoto, Japan*

³ *Department of Physics and Astronomy, University of Sussex, Brighton, BN1 9QJ, UK*

⁴ *ISCAP, Columbia University, Mailcode 5247, New York NY 10027, United States*

⁵ *Astronomy Centre, University of Sussex, Brighton, BN1 9QJ, UK*



Dark energy affects the CMB through its perturbations and affects both CMB and Sn Ia through its background evolution. Using recent CMB and Sn Ia data sets, together with the most general parametrization of the dark energy equation of state available, we find that today $w < -0.8$ (2σ). We also find that the value of the normalization of the power spectrum on cluster scales, σ_8 , can be used to discriminate between dynamical models of dark energy (Quintessence models) and a cosmological constant model (Λ CDM).

1 Introduction

The WMAP satellite measurements of the Cosmic Microwave Background anisotropies¹ have provided accurate determinations of many of the fundamental cosmological parameters. When combined with other data sets such as the luminosity distance to type-Ia supernovae or large scale structure (LSS) data^{2,3,4,5}, they reinforce the need for an exotic form of dark energy, which is characterized by a negative pressure and is responsible for the observed accelerated expansion of the universe. There are two main scenarios used to explain the nature of the dark energy, a time independent cosmological constant Λ , an evolving scalar field (Quintessence)^{6,7,8}. Previous tests of quintessence with pre-WMAP CMB data^{9,10,11}, have led to constraints on the value of the dark energy equation of state parameter, $w_Q \lesssim -0.7$ with the cosmological constant value, $w_\Lambda = -1$ being the best fit. Nevertheless a dynamical form of dark energy is not excluded. Specifically the detection of time variation of w would be of immense importance as it would rule out a simple cosmological constant scenario.

We perform a model independent analysis of the time evolution of the dark energy equation

of state. We conduct the likelihood analysis using the WMAP data¹ and the Sn Ia luminosity distance data^{2,3}.

2 Method and Data

We parametrize the equation of state w using five dark energy parameters (\overline{W}_Q). They are: the value of w today, w_Q^0 , its value at high redshift, w_Q^m , the value of the scale factor where w changes between these two values, a_c^m and the width of the transition, Δ . We are using the form advocated in Corasaniti & Copeland¹², which has been shown to allow adequate treatment of generic quintessence and to avoid the biasing problems inherent in assuming that w is constant.

We also include the cosmological parameters $\overline{W}_C = (\Omega_Q, \Omega_b h^2, h, n_S, \tau, A_s)$, which are the dark energy density, the baryon density, the Hubble parameter, the scalar spectral index, the optical depth and the overall amplitude of the fluctuations respectively. We are assuming a flat universe. We therefore end up with ten parameters which can be varied independently.

There is a degeneracy in n_S, τ and $\Omega_b h^2$, which allows the models to reach unphysically high values of the baryon density and the reionisation optical depth. Following the WMAP analysis we place a prior on the reionisation optical depth, $\tau \leq 0.3$. We also limit ourselves to models with $w(z) \geq -1$.

In order to compute the CMB power spectra, we use a modified version of the CMBfast Boltzmann solver¹³. Rather than using grid-based analysis (which would necessitate very coarse sampling), we opted for a Markov-Chain Monte Carlo (MCMC) approach. We ran 16 to 32 independent chains on the UK national cosmology supercomputer (COSMOS). This approach has both the advantage that there was no need to parallelize the Boltzmann solver, and lets us assess the convergence and exploration by comparing the different chains.

3 Results

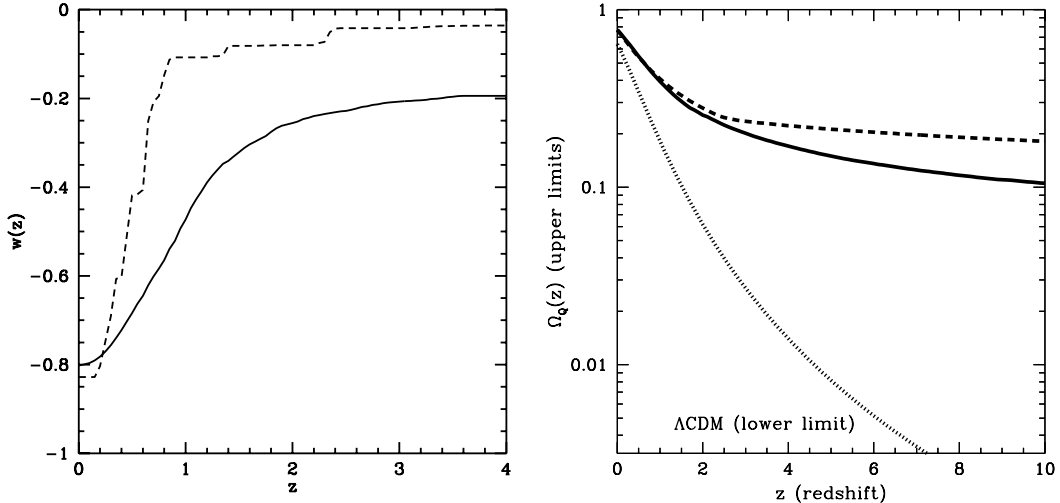


Figure 1: Upper 2σ limits on $w(z)$ (left) and $\Omega_Q(z)$ (right) derived by taking the 95% models with lowest $w(z)$ from our main chain (solid), searching for the highest $w(z)$ for models with $\Delta - \chi^2 < 4$ from the best-fit model in our main chain (dashed). Λ CDM is acceptable at 2σ and so there is no lower limit on $w(z)$.

Our global best fit QCDM model has the dark energy parameters $w_Q^0 = -0.99$, $w_Q^m = -0.11$, $a_c^m = 0.50$ and $\Delta = 0.079$, which corresponds to a fast transition at redshift of 1. The total χ^2 of the model is 1604, compared to the Λ CDM model $\chi^2 = 1606$. The number of degrees of freedom

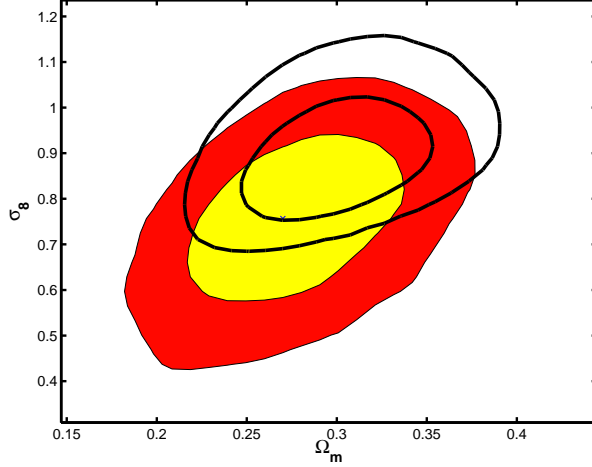


Figure 2: Marginalized 68% and 95% confidence contours for quintessence (filled contours) and Λ CDM models (solid lines). Λ CDM has a systematically higher value of σ_8 , and a slightly higher value of Ω_m .

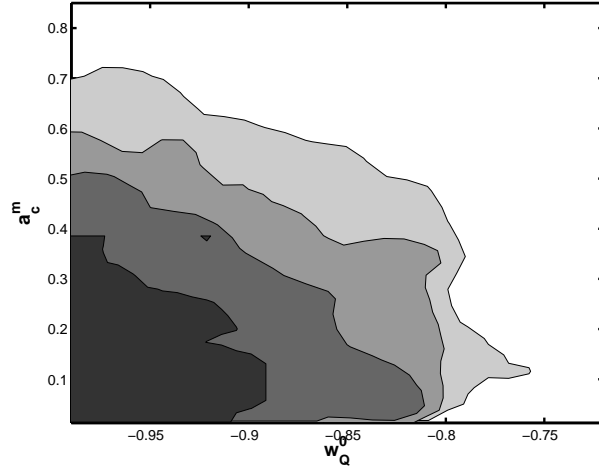


Figure 3: The 95% confidence regions for models with a rapid transition for different limits on σ_8 , going from (lightest grey to darkest) all data, $\sigma_8 > 0.75$, $\sigma_8 > 0.9$ and $\sigma_8 > 1.05$.

is 1514, so all our fits are bad, but this is mainly due to issues with the WMAP data (see the discussion in Spergel *et al.* ¹⁴).

The WMAP CMB data constrains the cosmological parameters \overline{W}_C in a range of values consistent with the results of previous analysis ^{14,15,16}. The addition of the dark energy parameters \overline{W}_Q does not introduce any new degeneracies with the other parameters. However, there are new internal degeneracies between the dark energy parameters. In particular the only parameter we can constrain well is the equation of state today $w_Q^m < 0.8$ at 2σ . A more complete discussion of this will be available in a forthcoming paper ¹⁷.

However, we have found that information about the power spectrum on cluster scales (σ_8), would allow us to break this degeneracy. In Corasaniti *et al.* ¹⁸ it was shown the different quintessence models leave a different imprint on the CMB power spectrum. Models with a more rapid transition at smaller redshifts will produce a larger ISW effect than Λ CDM. This means they require a smaller value of A_s to fit the CMB data, and so will have a smaller σ_8 . Figure 2 shows us that an independent measurement of σ_8 would allow us to distinguish between Λ CDM and a time dependent dark energy component.

This is shown in more detail in fig. 3. Here we plot the 95% confidence regions for rapid

transition models ($w_Q^m > -0.3$ and $a_c^m/\Delta > 1.2$ which includes our best fit model) with different limits on the value of σ_8 . Λ CDM will correspond to $w_Q^0 = -1$ and $a_c^m \rightarrow 0$, and so will sit in the bottom left-hand corner of this plot, favouring high- σ_8 models. As we move away from this corner, the limit on σ_8 falls. If we restrict ourselves to models with high- σ_8 we favour Λ CDM-similar models, while in the opposite case we can exclude them. For more discussion on this area see our previous paper¹⁹.

4 Conclusions

We have analyzed the dark energy with a model-independent approach using CMB and Sn Ia data. We have found that of our 4 dark energy parameters, only the equation of state today is well constrained, with $w_Q^0 < -0.80$. We also see no strong change in w for $z < 1$. There are no new degeneracies between our extra dark energy parameters and the other cosmological parameters. The degeneracies in the dark energy parameters may be broken using clustering data, which could ultimately be used to distinguish QCDM and Λ CDM. Nevertheless, there is no significant improvement over Λ CDM model.

Acknowledgments

MK and DP are supported by PPARC. BB is supported in Kyoto by the JSPS. We acknowledge extensive use of the UK National Cosmology Supercomputer funded by PPARC, HEFCE and Silicon Graphics / Cray Research.

References

1. C.L. Bennet *et al.*, *Astrophys. J. Suppl.* **148** 1 (2003).
2. S.J. Perlmutter *et al.*, *Astrophys. J.* **517**, 565 (1999).
3. J.L. Tonry *et al.*, *Astrophys. J.* **594** 1 (2003).
4. R.A. Knop *et al.*, *astro-ph/0309368*
5. G. Efstathiou *et al.*, *Mon. Not. Roy. Astron. Soc.* **330** L29 (2002).
6. C. Wetterich, *Nucl. Phys. B* **302**, 668 (1988).
7. I. Zlatev, L. Wang and P.J. Steinhardt, *Phys. Rev. Lett.* **82**, 896 (1999).
8. C. Armendáriz-Picón, V. Mukhanov, and P. J. Steinhardt, *Phys. Rev. Lett.* **85**, 4438 (2000).
9. P.S. Corasaniti and E.J. Copeland, *Phys. Rev. D* **65**, 043004 (2002).
10. S. Hannestad and E. Mortsell, *Phys. Rev. D* **66**, 063508 (2002).
11. B.A. Bassett, M. Kunz, J. Silk and C. Ungarelli, *Mon. Not. Roy. Astron. Soc.* **336**, 1217 (2002).
12. P.S. Corasaniti and E.J. Copeland, *Phys. Rev. D* **67**, 063521 (2003).
13. U. Seljak & M. Zaldarriaga, *Astrophys. J.* **469**, 437 (1996).
14. D.N. Spergel *et al.*, *Astrophys. J. Suppl.* **148** 175 (2003).
15. L. Amendola & C. Quercellini, *Phys. Rev. D* **68** 023514 (2003).
16. R.R. Caldwell, M. Doran, *astro-ph/0305334*.
17. P. S. Corasaniti, M. Kunz, D. Parkinson, E. J. Copeland and B. A. Bassett, *in preparation*.
18. P. S. Corasaniti, B. A. Bassett, C. Ungarelli and E. J. Copeland, *Phys. Rev. Lett.* **90**, 091303 (2003).
19. M. Kunz, P. S. Corasaniti, D. Parkinson and E. J. Copeland, *Phys. Rev. D*, *to appear*, *arXiv:astro-ph/0307346*.